National Aeronautics and
Space Administration

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California Institute of Technology
Pasadena, California

Observing fast mesoscale atmospheric processes with a geostationary microwave sounder

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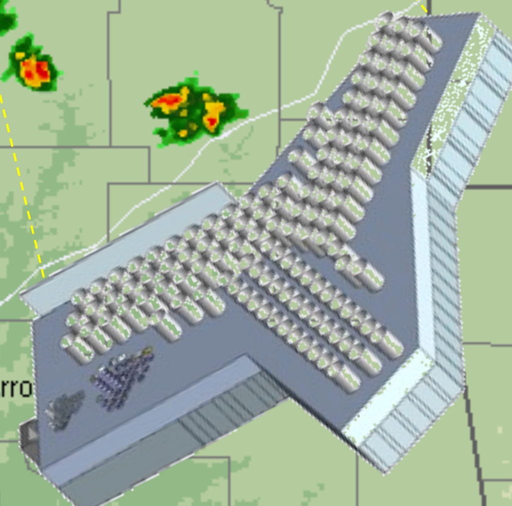
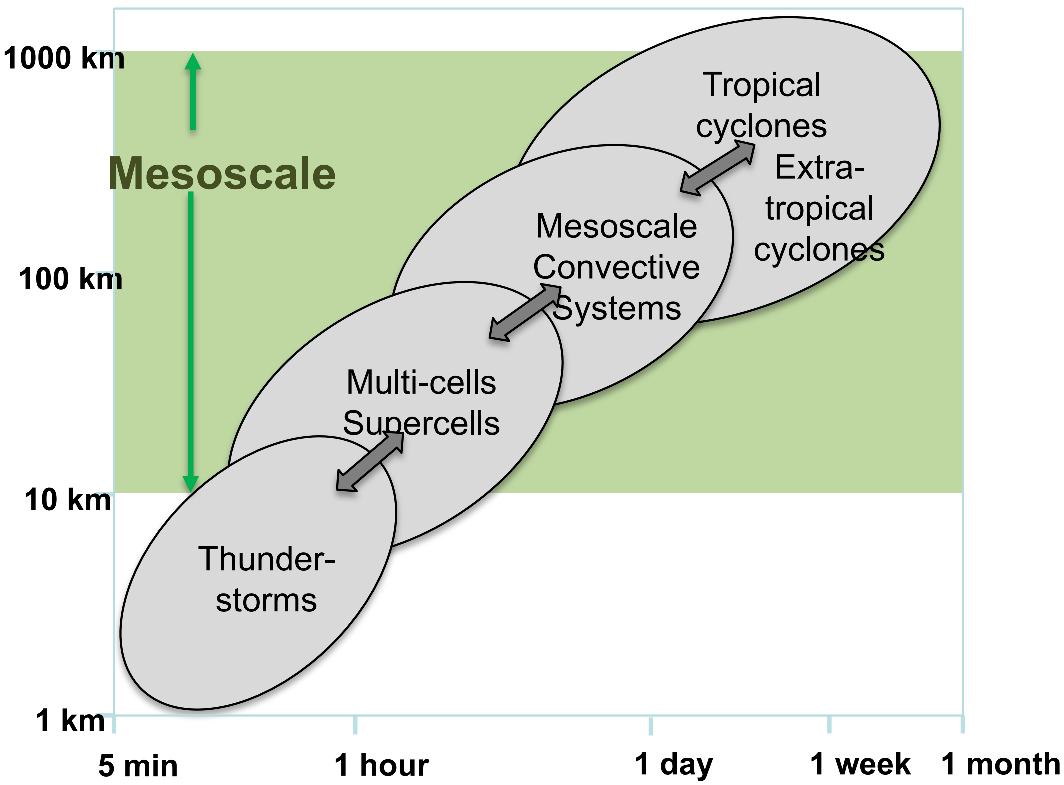


SPIE Asia-Pacific Remote Sensing – Honolulu, September 24-26, 2018

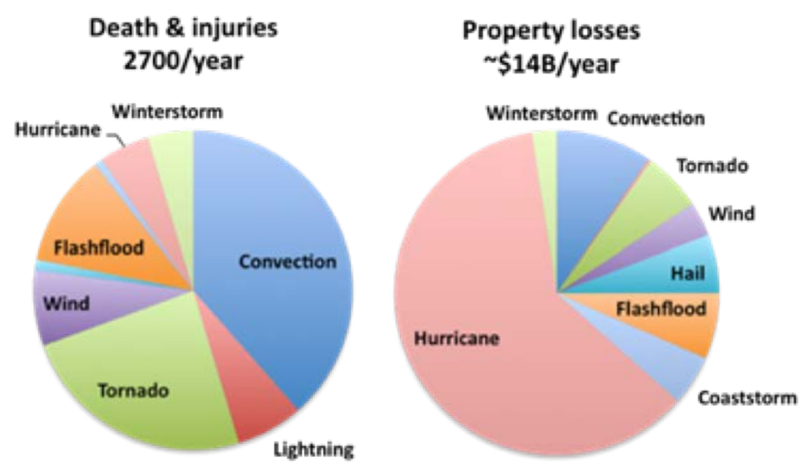
Focus: Severe storms

Hierarchy of convective storms & their building blocks
- Mesoscale Convective Systems
- Tropical & extratropical cyclones

All have fast processes, lifetimes range from hours to weeks
- Requires persistent observations



Severe storms cause tremendous damage
(U.S. storm losses 1998-2010 avg.)



Observing needs

General requirements for mesoscale storm observations

- All weather conditions: Observe through clouds and precipitation
- Horizontal resolution: Storm scale (~25-50 km) (≠ *Convective scale!)*
- Vertical resolution: Min. 3 layers (in-flow, cloud-formation, out-flow)
- Temporal resolution: Resolve rapid processes (~ 30 min; 5 min for intense precip.)
- Sampling frequency & density: Fully cover all key processes (pref. continuously)

Thermodynamics, defines the controlling environment

- Vertical profiles of temperature and water vapor (soundings)
- Cloud parameters: extent, liquid & ice water content, cloud top temperature

Convection, represents the most dynamic & energetic aspects

- Vertical structure & intensity: Reflectivity profiles
- Precipitation: Surface rain rate, vertical distribution
- Microphysics: Particle size distribution
- Vertical transport: Vertical velocity

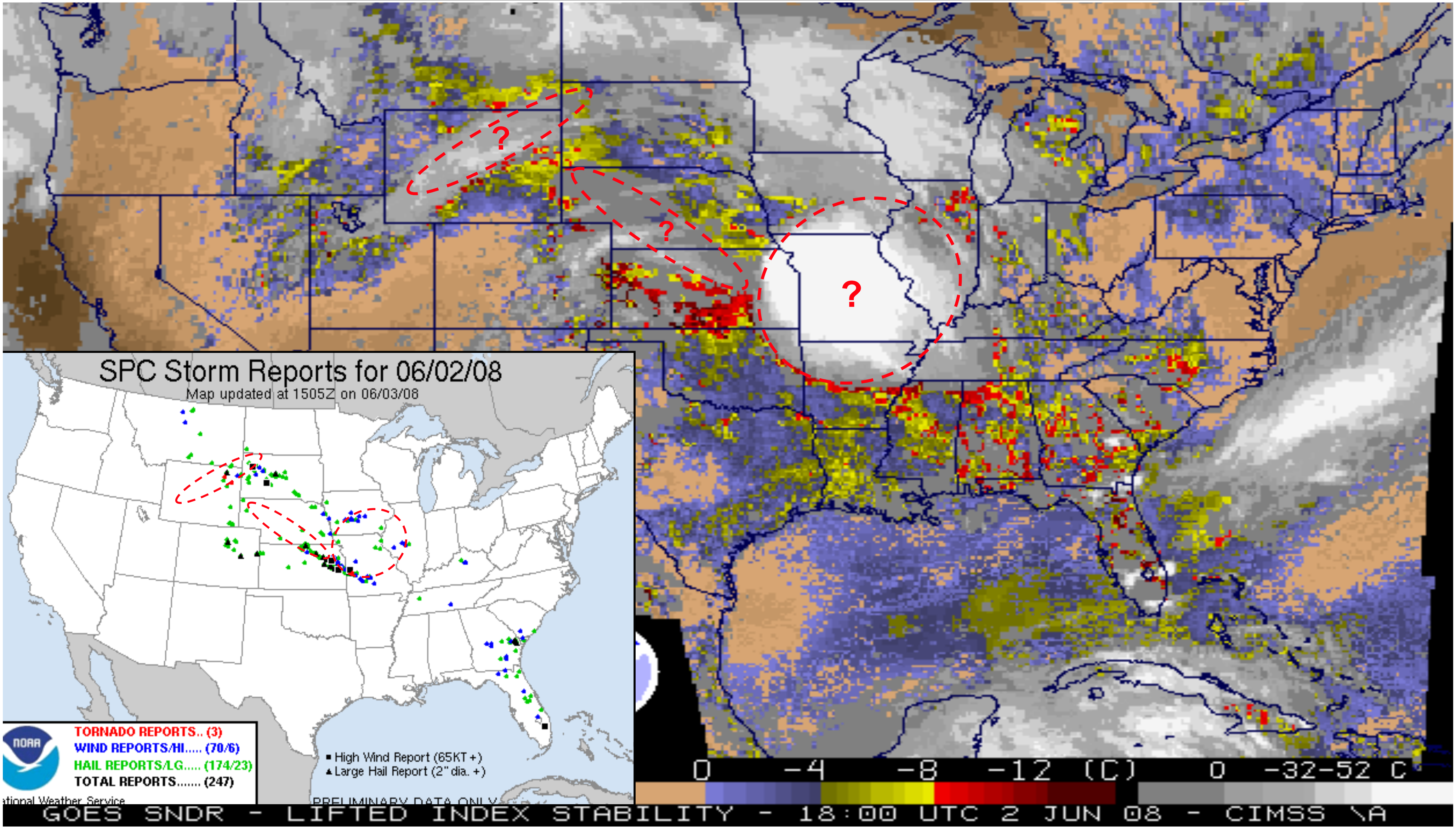
Wind, represents fluxes and storm motion

- Horizontal transport: Horizontal wind velocity

What's going on below those clouds?

Current capabilities: Poorly observed; infrequently sampled; poorly modeled

GEO/MW capabilities: *All* conditions, observations *in* storms; every 15 minutes



Current storm sensors: Inadequate

None of the current observing systems are adequate:

- LEO satellites do not have adequate revisit times
- IR GOES cannot penetrate clouds
- None observes thermodynamics, wind and rain at the same time

However: A GEO MW-sounder can meet almost all requirements

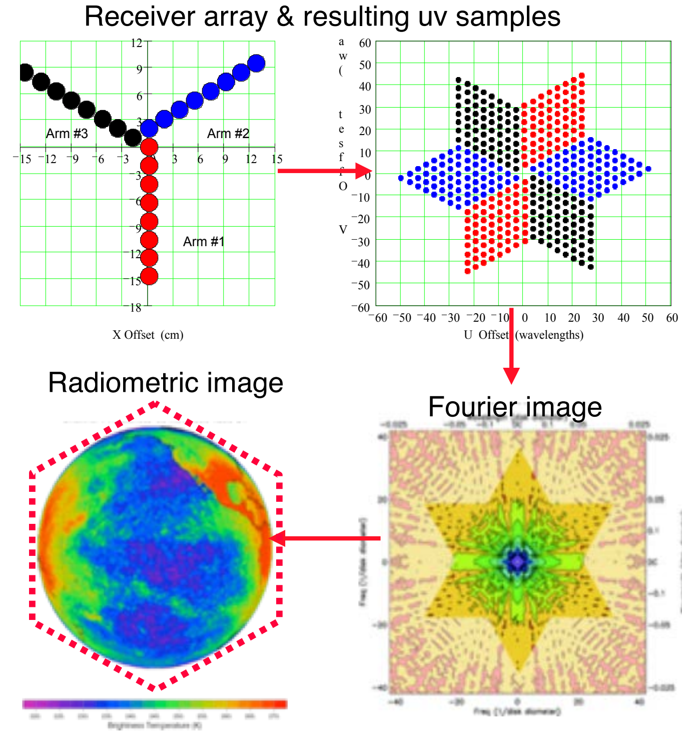
Sensor system	Continuous	All-weather	Full coverage	Thermodyn.	Precipitation	Wind	Microphysics
Ground radar (NEXRAD)	+	+	0	X	+	0	+
GEO imagers (GOES-16)	+	X	+	X	X	0	X
LEO MW-sounders (ATMS)	X	+	0	+	+		0
LEO MW-imagers (SSM/I)	X	+	0	X	+	0	0
LEO IR-sounders (AIRS, CrIS)	X	X	0	+	X	X	X
LEO radar (GPM)	X	+	0	X	+	X	+
GEO MW-sounder (GeoSTAR)	+	+	+	+	+	+	0

+ = capable, 0 = partially capable, X = incapable

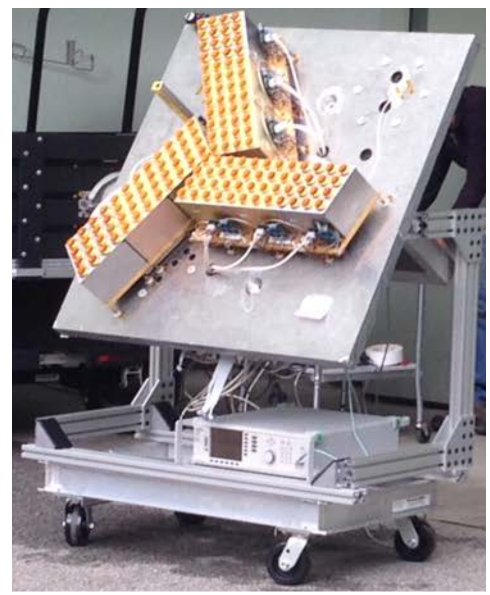
The GeoSTAR concept

- **Aperture-synthesis concept**
  - Sparse array employed to synthesize large aperture
  - Cross-correlations -> Fourier transform of Tb field
  - Inverse Fourier transform on ground -> Tb field
- **Array**
  - Optimal Y-configuration: 3 sticks; N elements
  - Each element is one I/Q receiver, 3.5λ wide (2.1 cm @ 50 GHz; 6 mm @ 183 GHz!)
  - Example: N = 100 ⇒ Pixel = 0.09° ⇒ 50 km at nadir (nominal)
  - One "Y" per band, interleaved
- **Other subsystems**
  - A/D converter; Radiometric power measurements
  - Cross-correlator - massively parallel multipliers
  - On-board phase calibration
  - Controller: accumulator -> low D/L bandwidth

This is the only viable "array spectrometer" design and is what the NRC had in mind in the 2007 "decadal survey"



Proof-of-concept prototype developed at JPL



What can we measure with GeoSTAR?

TIME TESTED MEASUREMENTS AND DATA PRODUCTS USING MATURE ALGORITHMS

GeoSTAR will make similar measurements from GEO as AMSU/ATMS currently does from LEO, but every ~15 minutes vs. 2 times per day

High-intensity precipitation can be sampled in 5 minutes or less

GeoSTAR would uniquely provide measurement of

Temperature/moisture/clouds; Wind; Precipitation

…simultaneously, continuously, 3D, all-weather…

Parameter	Horizontal	Vertical	Temporal	Precision	Accuracy	Thermodyn.	Bulk microphys.	Dynamics
Brightness temperatures	25 - 50 km ↓ 10-20 km (see next slide)	N/A	5-20 min.	0.5-1.5 K	0.5 K			
Temperature	25 - 50 km ↓ 10-20 km (see next slide)	2-3 km	5-20 min	1.5 K	0.5 K	√		
Water vapor				25%	10%	√		
Wind vector (u,v)				2 m/s	1 m/s			√
Reflectivity				4 dBZ	2 dBZ		√	
Rain rate		N/A		3 mm/hr	50%	√	√	
LWP				25%	10%	√		
IWP				25%	20%	√	√	

Precision & accuracy reflect performance of MIRS (except for reflectivity)

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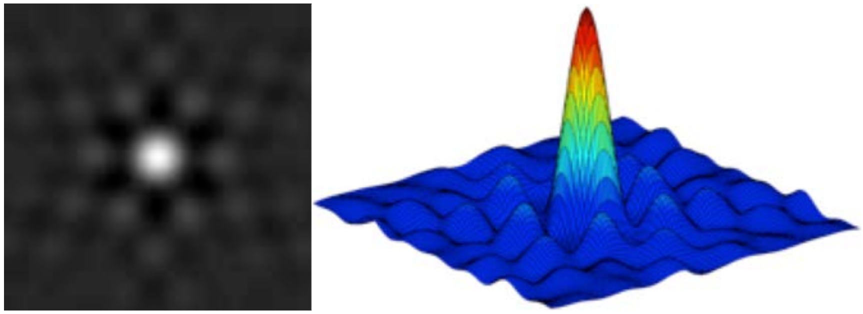
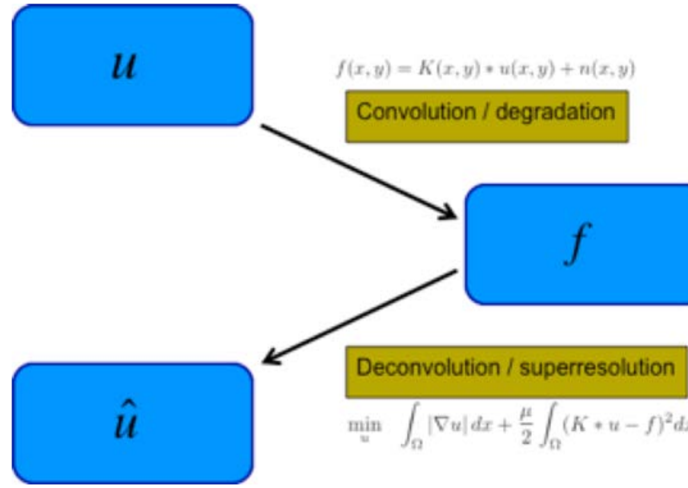
Resolution enhancement: 25 → 10 km

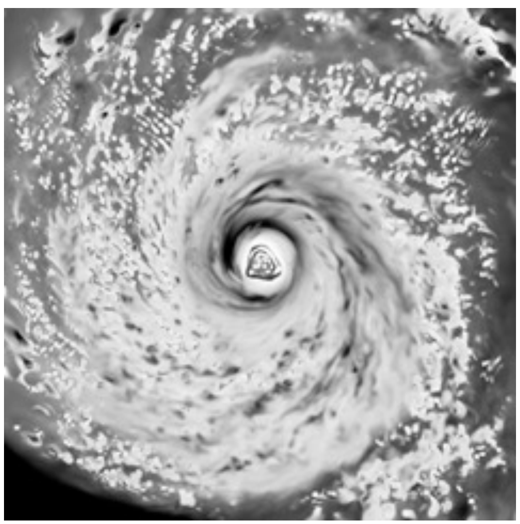
Total Variation Image Restoration: Split Bregman Method

Yanovsky, Lambrigtsen, Tanner, Vese, *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 2015*

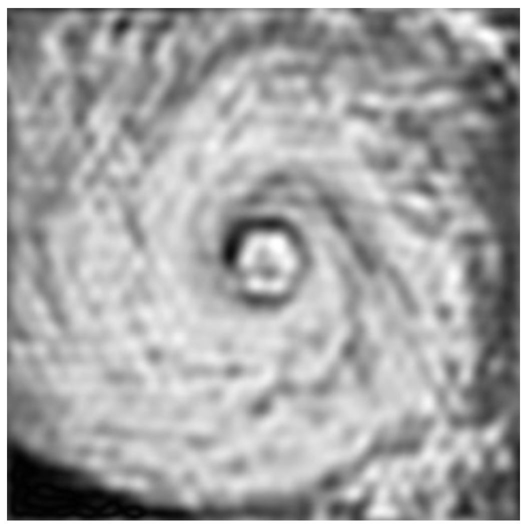


GeoSTAR PSF

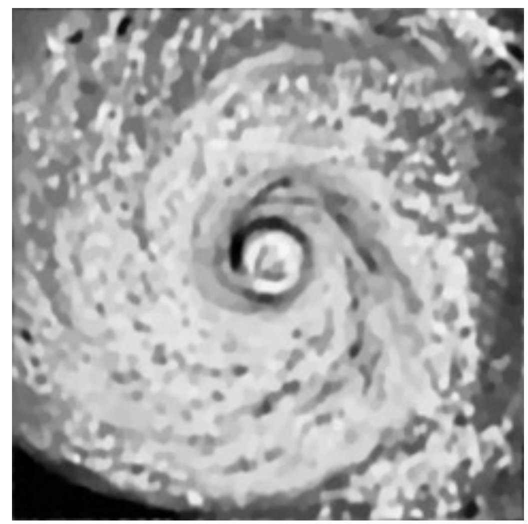




Original clean image



Blurry and noisy image



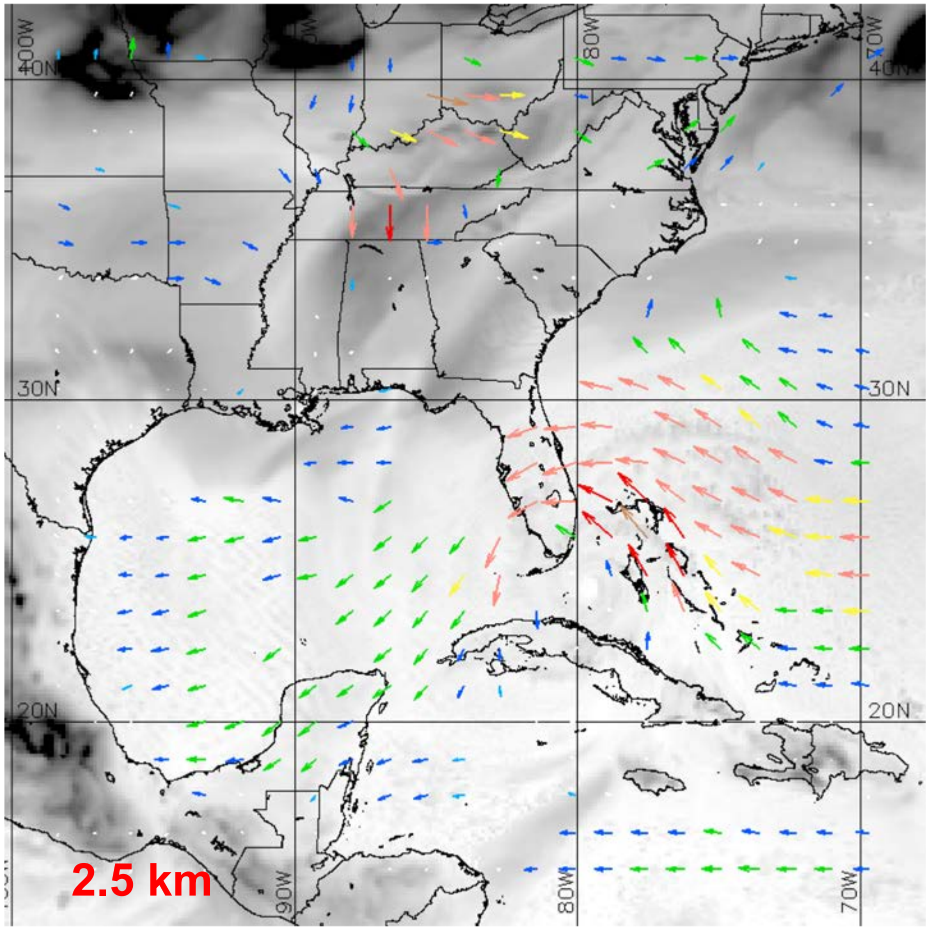
Reconstructed image

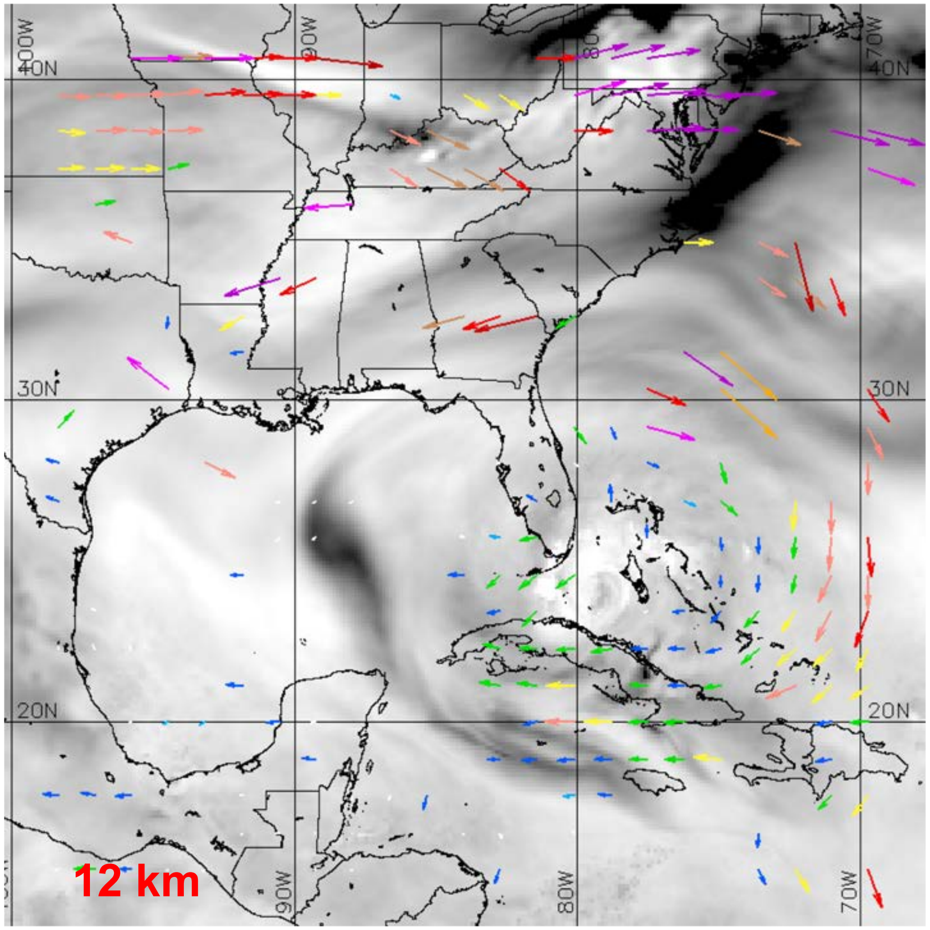
This approach is feasible because of the heavily oversampled nature of STAR imagery
It can also be applied in the time domain to increase effective sampling frequency

Product highlight: Wind vectors

Height-registered wind vectors will be derived from water vapor features (AMVs)
Based on method developed at U. Wisconsin (Velden et al.)
GeoStorm will provide u,v wind maps @ 25 km x 3 km resolution in 3-D every 15 minutes!

WRF simulation of Rita (2005)



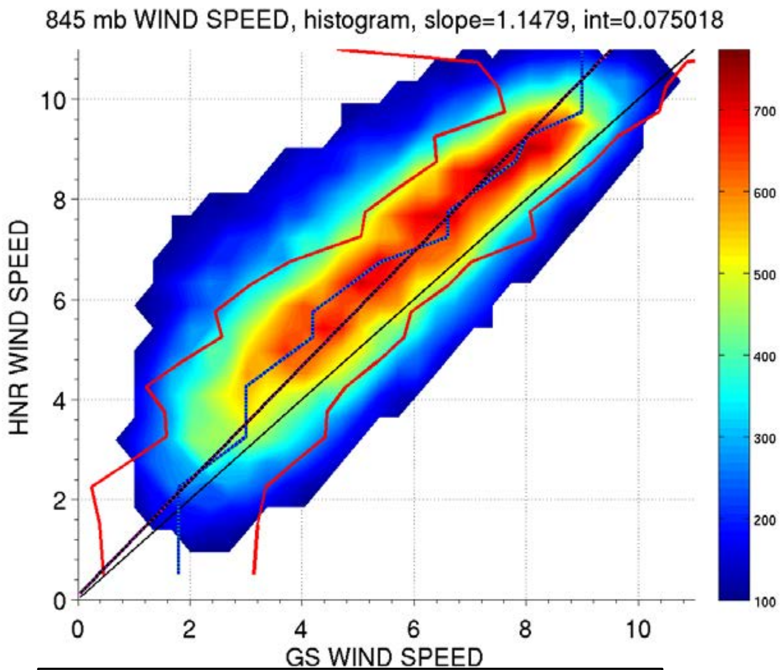


Credit: S. Hristova-Veleva & J. Turk, JPL

Wind simulation results

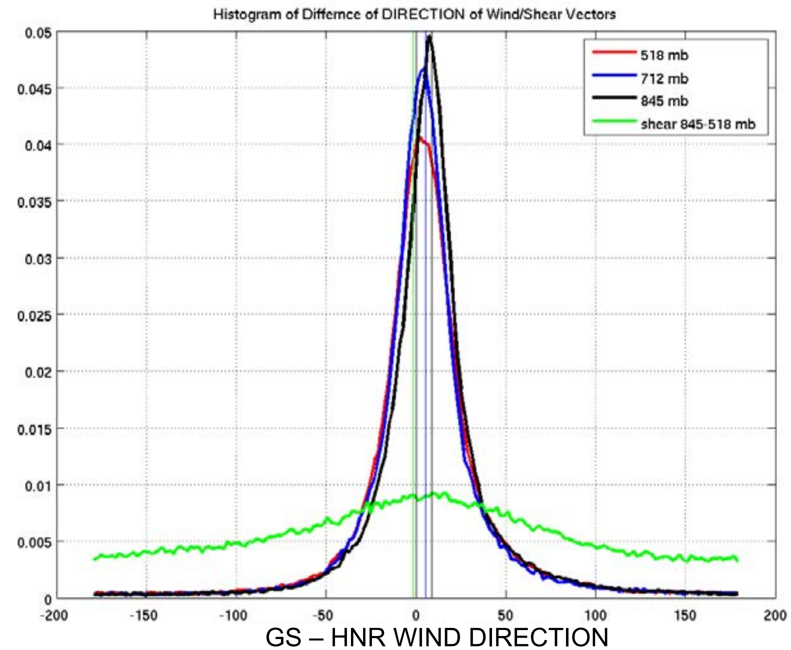
Based on large sample size (> 5000); cases with rain rate < 1 mm/hr

Wind speed: Histogram @ 845 mb



Red lines indicate 1-sigma levels
Black line: Best fit, nearly linear
Precision (rms) = 1.7 m/s; bias = -1 m/s

Wind direction: 3 pressure levels



Direction at 3 pressure levels
Also showing wind shear
Precision (rms) < 15° ; bias < 6°

Summary:
Precision < ± 2 m/s - This meets WMO requirements for wind

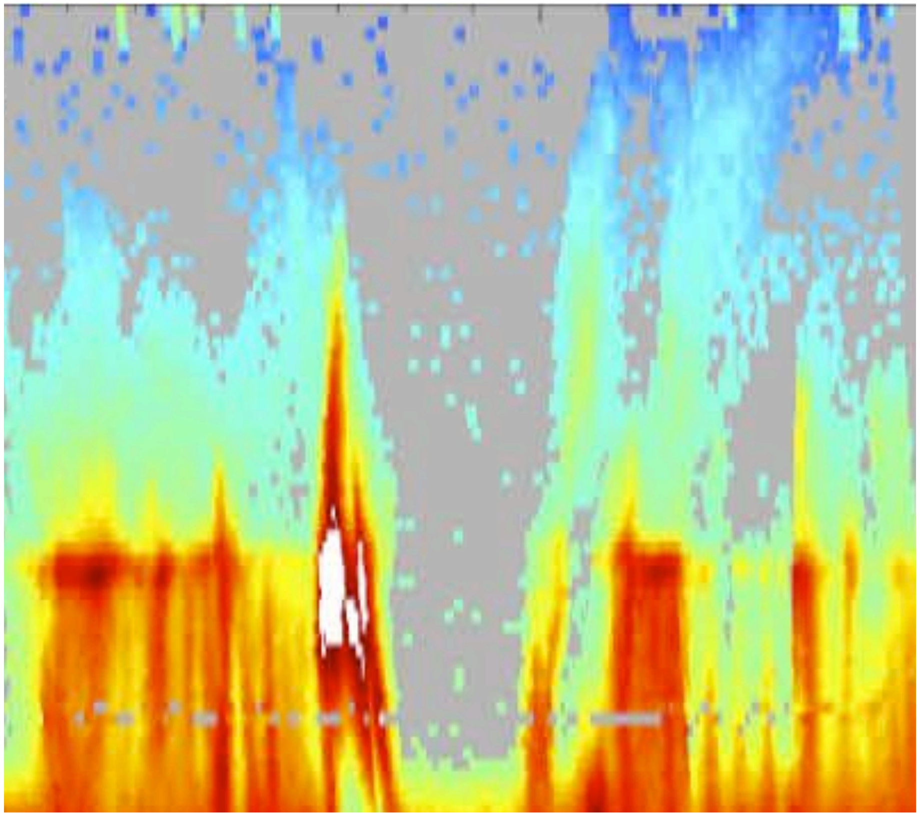
Pressure level (mb)	Bias		RMS error	
518	-0.8 m/s	2°	1.9 m/s	14°
712	-1.2 m/s	3°	1.6 m/s	11°
845	-1.0 m/s	6°	1.7 m/s	10°

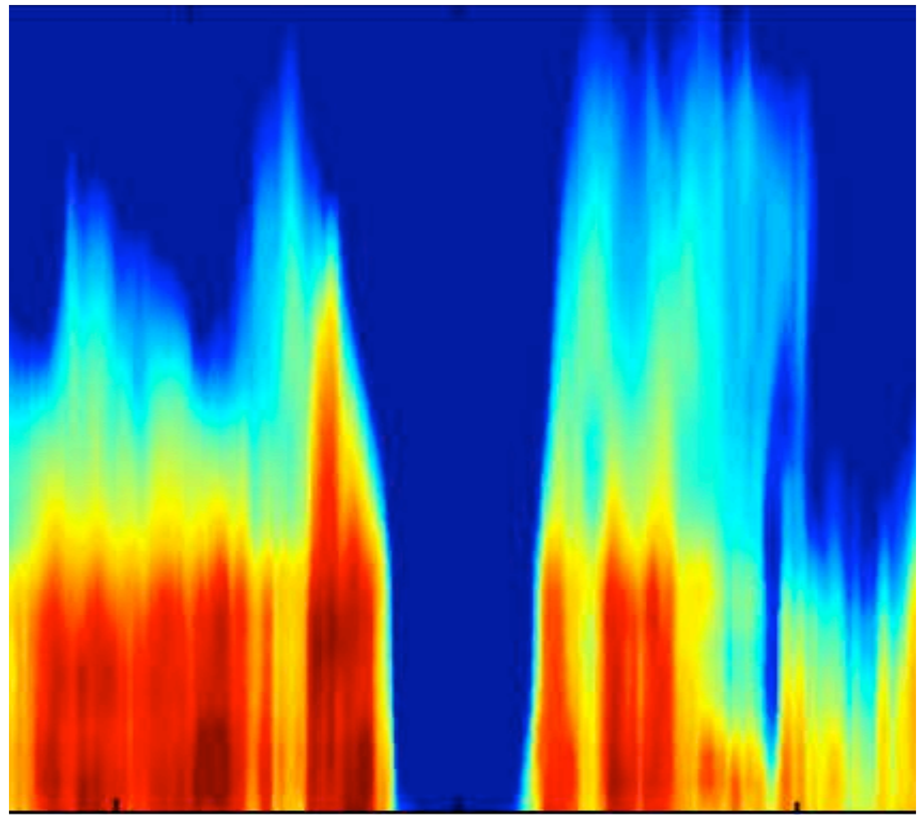
Product highlight: Reflectivity

An algorithm has been developed to produce reflectivity profiles from MW sounder data

Images below show real radar (left) vs. MW product (right) from an aircraft campaign
Our product has less vertical resolution (1-2 km) and less sensitivity (~ 4 dBZ) than the radar, but all major features are accurately reproduced.

GRIP: H. Karl, eye pass #16 (0644 UTC 9/17 2012)





HIWRAP (radar)

Note: No space-time mismatch since both sensors are on same aircraft

HAMSR (MW sounder)

Reflectivity from satellite MW sounders!

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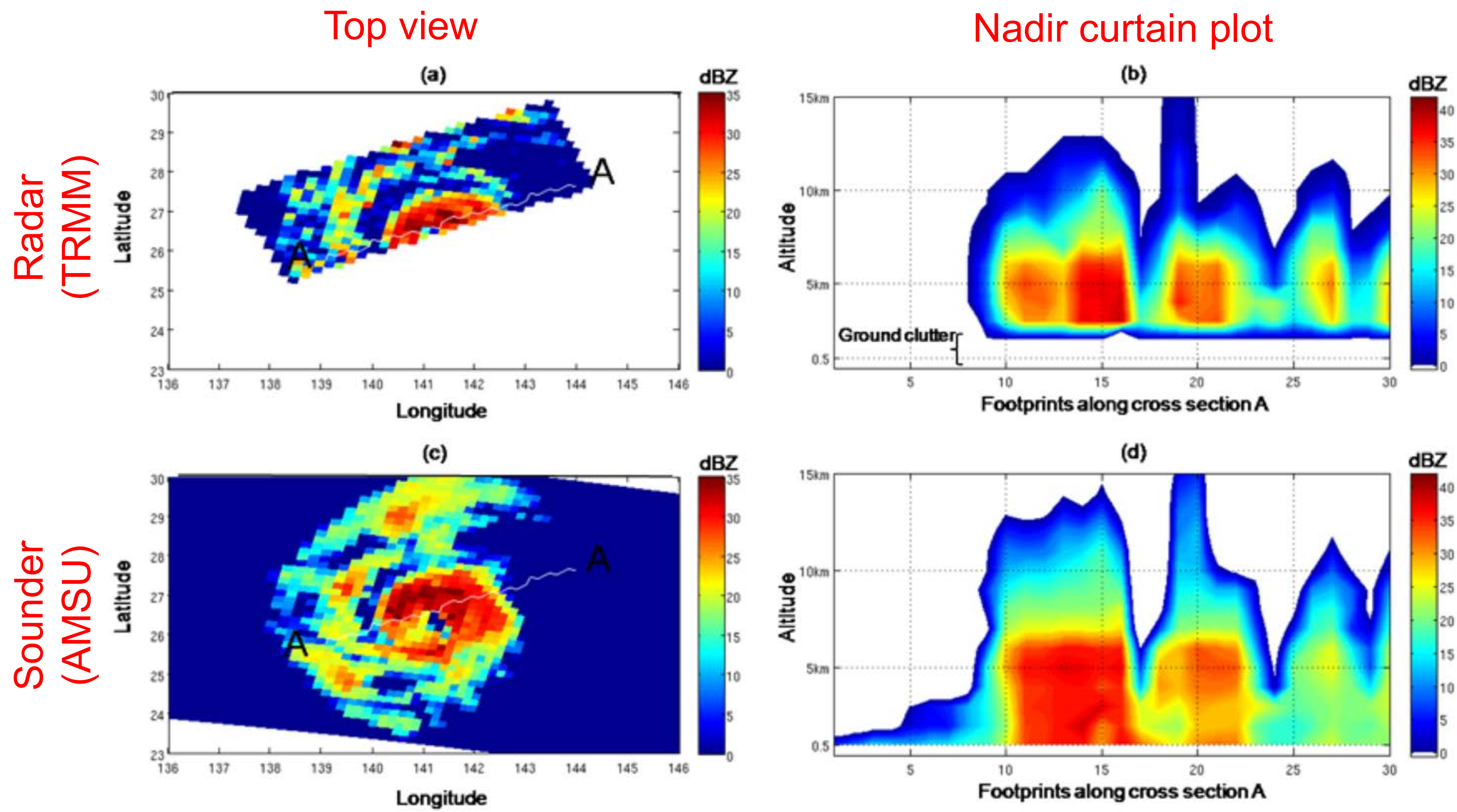
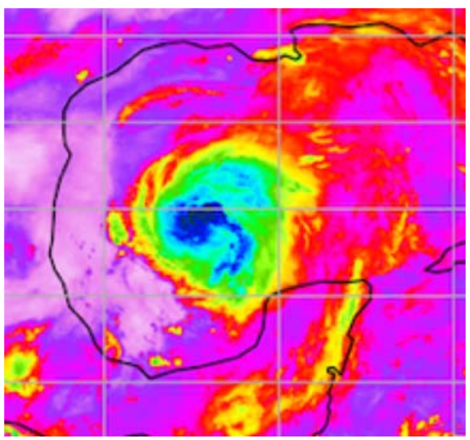
In this example we compare reflectivity derived from AMSU-A/B on NOAA-16 with nearly coincident (~10 min) reflectivity from the TRMM radar (averaged to 15 km, equivalent to AMSU-B) over Typhoon Saola off SE Japan on September 22, 2005



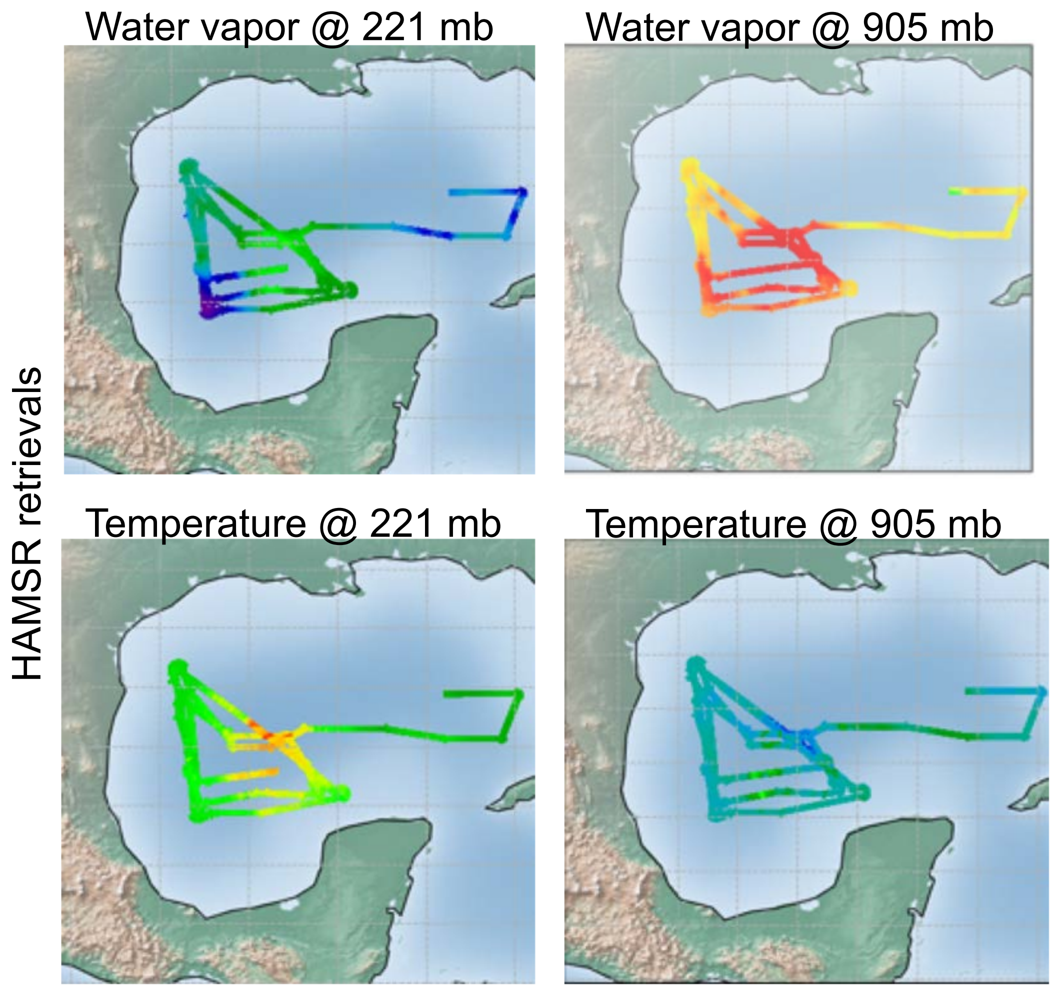
Soundings through precipitation

- A new retrieval algorithm has been developed at JPL (M. Schreier) which accounts for scattering and obtains temperature & water vapor profiles even in the presence of heavy precipitation
- The example below presents retrievals from the HAMSR aircraft-based MW sounder flying over Hurricane Harvey on August 24, 2017 and shows no discontinuities or anomalies in the presence of deep convection

Satellite view



ATMS Channel 3 Tb

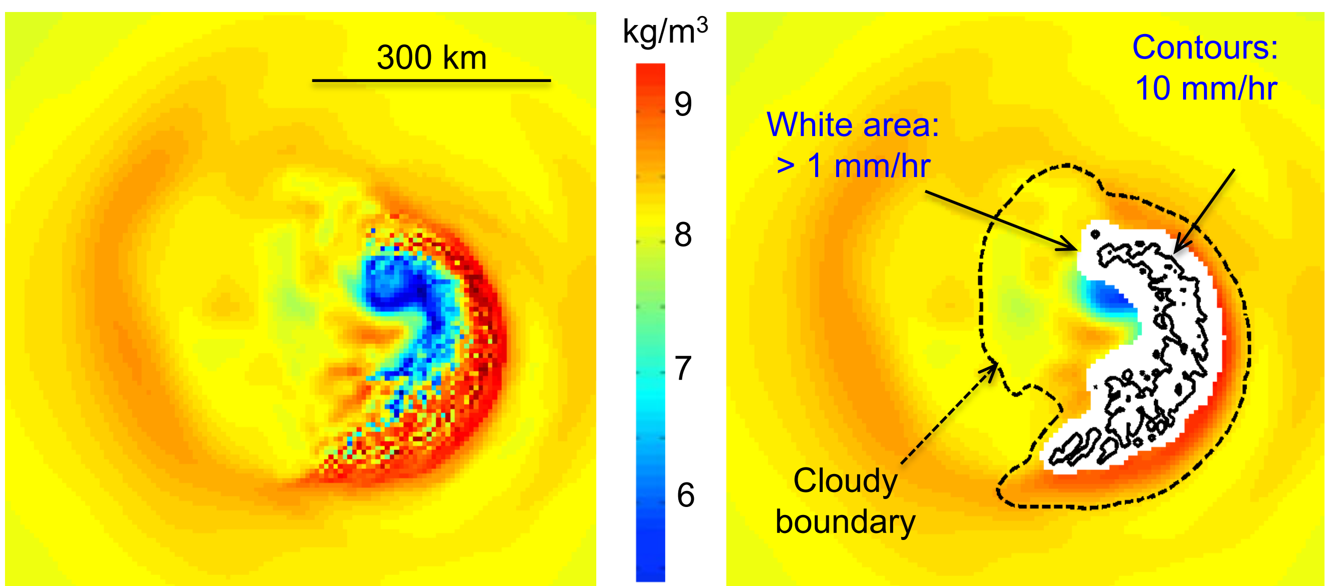


Penetrates clouds and precipitation

We can therefore fully dissect severe storms such as MCS's, as in example below

This illustrates an MCS simulation (water vapor near the surface) – left panel
The right panel shows what GeoSTAR will observe at 25 km resolution

- We will obtain retrievals everywhere, except at very high rain rates
- The broken line indicates the extent of clouds, where IR sensors are blind
- The white area indicates where the rain rate exceeds 1 mm/hr
- The solid black line shows the area where the rain rate exceeds 10 mm/hr
- GeoSTAR retrievals will be valid everywhere except in patches inside the black line



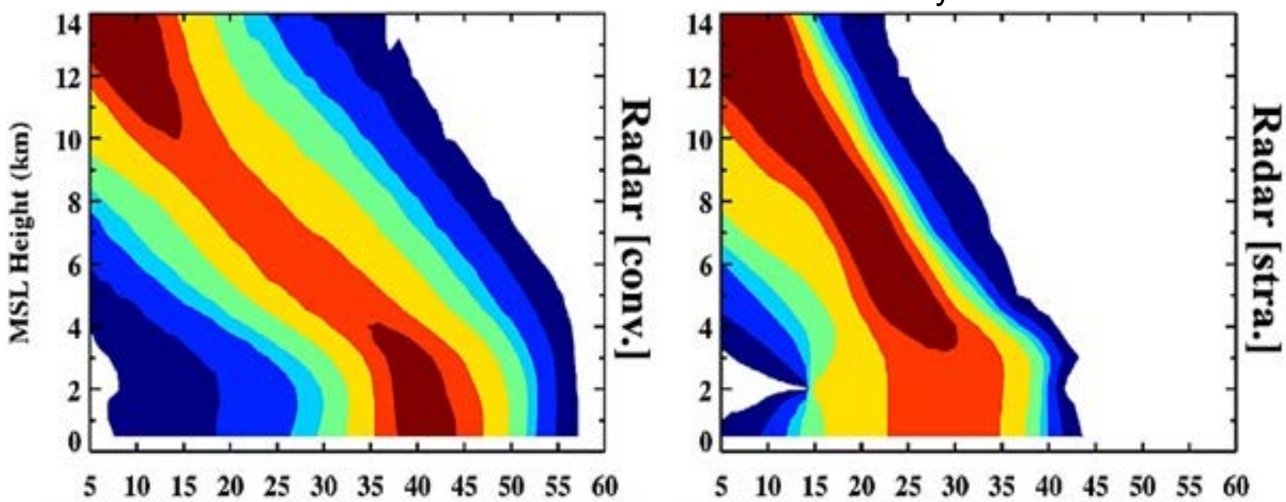
Model (6 km res.) GeoStorm (25 km res.)

Example: Stratiform vs. convective rain

The ability to discriminate between convective and stratiform rain is crucial in storm science

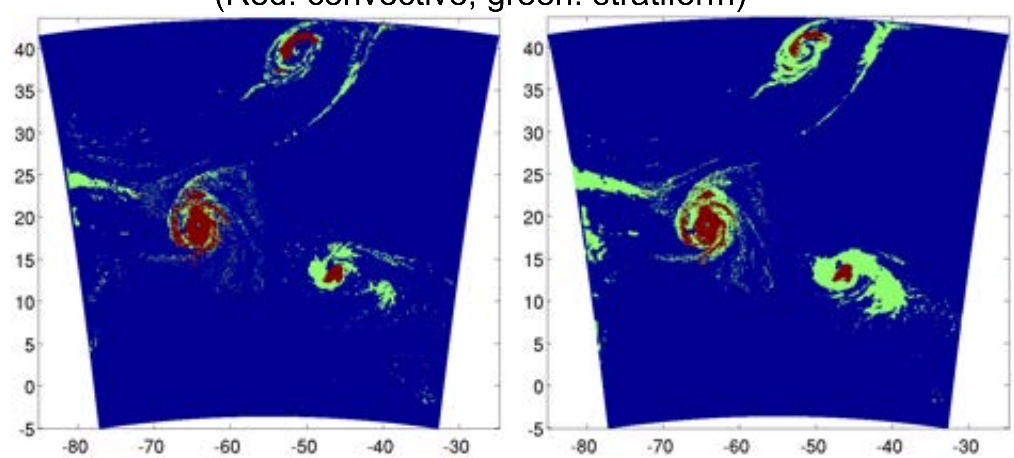
- Method 1: Reflectivity-profile histograms (CFADs) – derived from GeoSTAR reflectivity
- Method 2: IWP to LWP ratio – both are GeoSTAR sounding products
- Method 3: AMSU-B method – can be mimicked with GeoSTAR brightness temperatures

Convective vs stratiform discrimination with reflectivity CFADs



Convective vs stratiform discrimination with AMSU-B method
(Red: convective, green: stratiform)

AMSU-B →

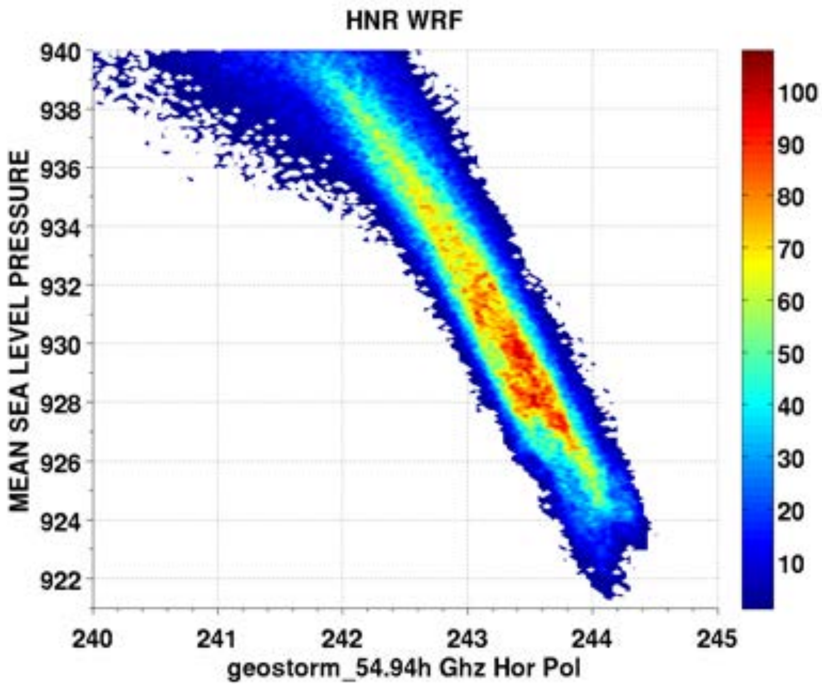


← GeoSTAR

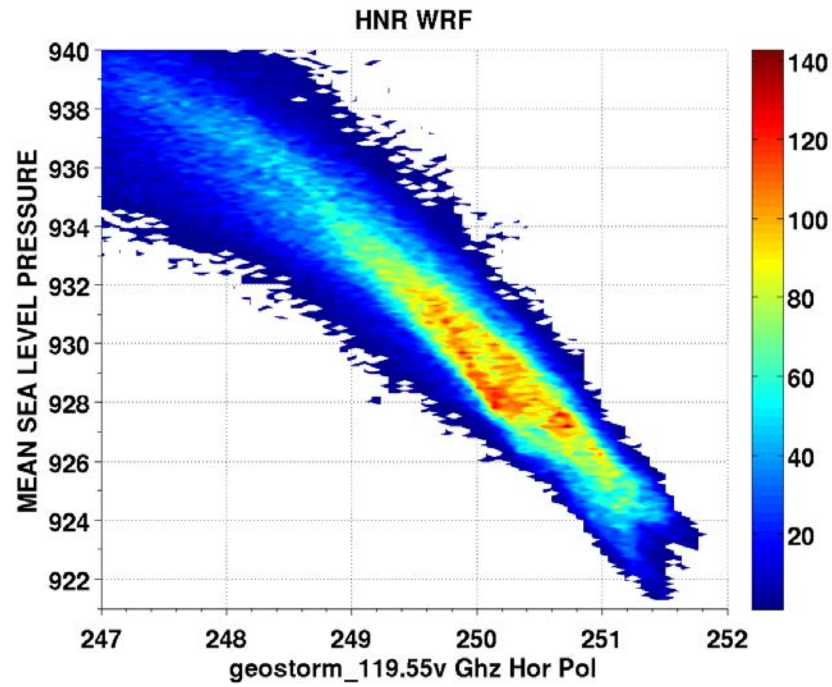
Example: Tropical cyclone intensity

- GeoSTAR will get "clean" sounding in most tropical cyclone eyes
- Measure warm core anomaly directly → Intensity from ΔT ←→ Intensity relationship
- Measure it indirectly from ΔTb ←→ Intensity relationship (derived from AMSU-A)

Simulation results from a NOAA hurricane nature run (HNR) showing precision (pdf) of the third method



Using the AMSU-A method



Using and equivalent 118-GHz channel

With GeoSTAR we can measure the intensity continuously and easily detect rapid intensification

Many high-value applications

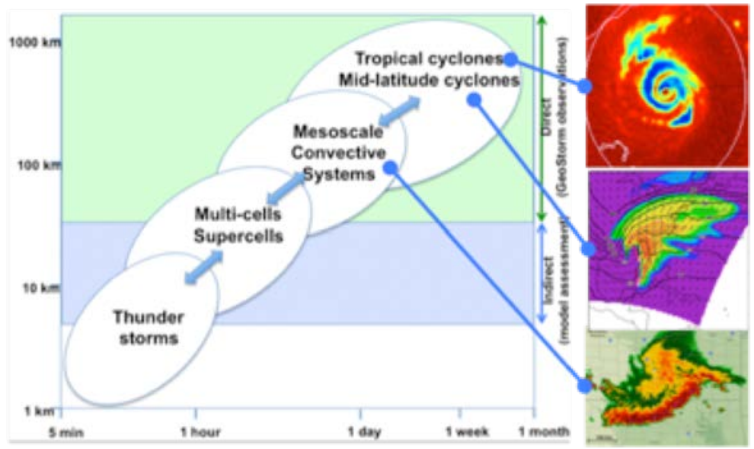
Application Usage	**Potential users**	Tb(chan)	T(z), q(z)	r(t), rtot	Z(z)	u(z), v(z)
Research Storm processes, hydrologic cycle	NASA, NOAA	√	√	√	√	√
Weather forecasting Assimilate: Improved storm predictions	NOAA, DoD, comm'l	√				√
Now-casting R/T storm obs: Intensity, path, rainfall totals	DoD, NOAA, FEMA, news	√	√	√	√	√
Aviation R/T flight conditions: Convection, icing, wind	FAA, airlines, civil air		√		√	√
Agriculture Growing conditions: Rain, wind, temperature	Farmers, insurance cos.		√	√		√
Transportation Storm path, flooding potential	Railways, truckers, public			√		√
Health Conditions for mosquitos, air pollution events	Health care providers		√	√		√
Water resources Rainfall totals: River flow predictions	Resource mgrs, responders			√		

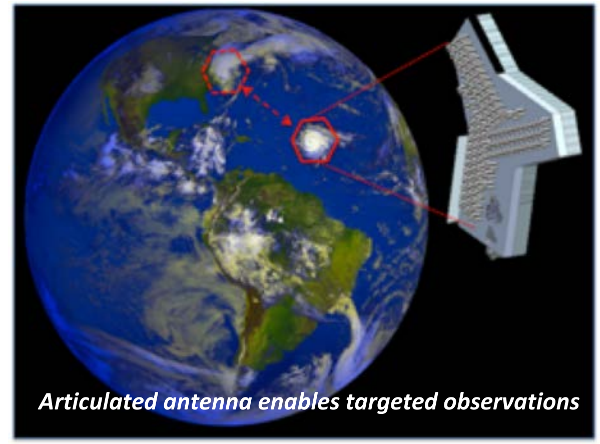
A low-cost GEO/MW mission concept

GEOSTORM: A GEOSTATIONARY MICROWAVE SOUNDER MISSION FOCUSED ON THE EVOLUTION OF SEVERE STORMS

Improve our understanding of sudden and unpredicted change in intensification and motion of destructive storms:

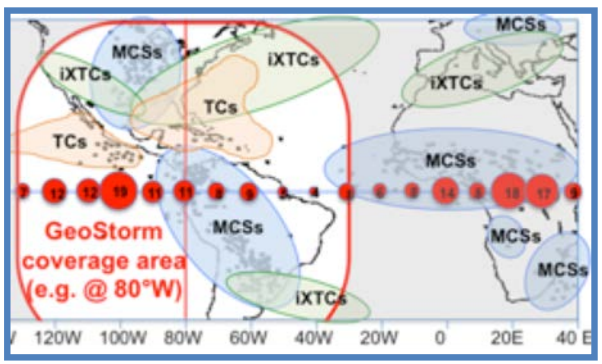
- ***hurricanes***
- ***severe thunderstorms and mesoscale convective systems***
- ***mid-latitude cyclones and winter storms***





Low cost as a hosted payload

Many hosting opportunities in GEO:



There are more than 80 GEO comm-sats that provides a view of the Americas, being replaced at a rate of 5-6 per year

GeoStorm Highlights	
Targeted observations	Life cycle storm tracking
Time-continuous	Capture dynamic processes; diurnal cycle fully resolved
Multiple simultaneous key parameters	Temperature, humidity, precipitation, wind
All-weather	Cloud/rain-penetrating
3-D observations	1000 km dia x 15 km vert. (volume); 25 km dia x 3 km vert. (resolution)
Wide coverage	All storms visible from GEO

"GeoStorm" implements a small version of GeoSTAR and requires articulation to cover the Earth disc
A full-size version of GeoSTAR will cover the entire Earth disc without articulation
Hosting on a commsat minimizes mission cost

Summary

The need for better severe-storm observations is critical

A GEO microwave sounder will meet most of the needs

The required technology is now ready

We can proceed with a storm-observing mission